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Strong [O III] and [N II] emission lines in globular clusters from photoionized R Corona Borealis star winds

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ABSTRACT
The globular cluster X-ray source CXO J033831.8-352604 in NGC 1399 has recently been found to show strong emission lines of [O III] and [N II] in its optical spectrum in addition to ultraluminous X-ray emission with a soft X-ray spectrum. It was further suggested that this system contained an intermediate mass black hole which had tidally disrupted a white dwarf, producing the strong emission lines without detectable hydrogen emission. We show that an alternative exists which can explain the data more naturally in which the oxygen and nitrogen rich material is ejecta from a RCB star, or a tidal disruption of an RCB star or a hydrogen-deficient carbon star. The scenario we propose here does not require an intermediate mass black hole as the accretor, but also does not exclude the possibility.

Key words: stars:winds,outflows – stars:peculiar – galaxies: star clusters: individual – X-rays:individual:CXOJ033831.8 - 352604

1 INTRODUCTION

The discovery of globular cluster X-ray sources in the Galaxy (e.g. Clark 1975) in the mid-1970's prompted the suggestion that X-ray emission might come from accretion onto intermediate mass black holes (Bahcall & Ostriker 1975 – BA75; Silk & Arons 1975 – SA75). It has since been shown that all the bright Galactic X-ray sources are likely to have neutron star accretors – all but one of them show pulsations and/or surface thermonuclear runaways (Liu et al. 2007 and references within; see also Altamirano et al 2010). The other has been the subject of Doppler tomography which favours a neutron star accretor, and rules out an intermediate mass black hole accretor (van Zyl et al. 2004). The mechanism suggested by BO75 and SA75 is nonetheless still potentially relevant for extragalactic globular cluster X-ray sources, as well as for faint X-ray (Ho et al. 2003) and radio (Maccarone 2004) sources in Galactic globular clusters. Recent work has suggested fueling of such black holes through tidal destruction of stars, which may be an effective way to provide more material in the vicinity of the black hole than standard stellar mass loss provides (e.g. Rosswog et al. 2009).

It has long been realized that the large globular cluster populations of nearby giant elliptical galaxies made them potentially rich targets for searching for globular cluster X-ray sources (Fabian, Pringle & Rees 1976). The *Einstein* observatory had the sensitivity and angular resolution to detect bright non-nuclear point sources in nearby galaxies, but only with the launch of *Chandra* has it been possible to localize such sources well enough to make reliable associations between the X-ray sources and globular clusters at distances beyond that of M 31. In recent years, several strong candidates for black holes in globular clusters have been identified (Maccarone et al. 2007; Brassington et al. 2010; Irwin et al. 2010; Shih et al. 2010; Maccarone et al. 2010). Two particularly interesting globular cluster X-ray sources show strong optical emission lines. The first, in NGC 4472, shows highly variable emission, peaking at about 4×10^{39} ergs/sec, confirming that the bulk of the emission comes from a single X-ray source (Maccarone et al. 2007), and strong, broad [O III] lines, with the lack of a clear detection of Hβ emission implying a ratio of oxygen to hydrogen much larger than that of solar composition material (Zepf et al. 2007,8; Steele et al. 2010, submitted to ApJ). The second, CXOJ033831.8 - 352604 in the Fornax xluster galaxy NGC 1399 is a bit fainter ($L_X \approx 2 \times 10^{39}$ ergs/sec), and has not shown strong variability, but shows strong emission lines from both [O III] and [N II] – although these lines are substantially fainter and narrower than the lines seen from RZ 2109 (Irwin et al. 2010 – I10). I10 argued that the properties of this source could be explained by tidal disruption of a white dwarf by an intermediate mass black hole. In this letter, we discuss a new interpretation for this system – that the globular cluster contains an RCB star, the wind of which is photoionized by the X-ray source.

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2 DATA

We present no new data in this paper, but do review the observational findings of I10 for the benefit of the reader. They report three X-ray observations with at least 100 counts, all showing an X-ray luminosity of $1.5 - 2.3 \times 10^{39}$ ergs/sec and good spectral fits with models of power laws with Γ in the 2.5-3.0 range, or disc blackbodies (Mitsuda et al. 1984) with KT_{in} of 0.36-0.39 keV.

They made several optical spectra. They find emission lines of the [O III]λ 5007 doublet and the [N II] λ 6584 Å doublet. They report HWHM of the lines to be 70 km/sec and their plots show a peak flux density in [O III]λ 5007 Å of 1.7×10^{-18} ergs/sec/cm^2/Å corresponding to a luminosity of about 2.0×10^{35} ergs/sec, given the 70 km/sec HWHM and in [N II] 6584 Å of 2.0×10^{-18} ergs/sec/cm^2/Å, corresponding the a luminosity of about 2.5×10^{35}ergs/sec. No other lines are found in this spectrum (J. Irwin, private communication). Visual inspection of their plots shows a noise level of about 3×10^{-19} ergs/sec/cm^2/Å, so we can set as targets for photoionization calculations that the luminosity in the main peaks of [O III] and [N II] are roughly similar, and both at about 2×10^{35} ergs/sec, and that any other lines in the optical bandpass should be no more than about half the strength of those two lines.

3 THE PROBLEM WITH THE DISRUPTED WHITE DWARF SCENARIO

The key problem with the intepretation of I10, which they noted, but did not resolve, is that the nitrogen emission lines are stronger than the oxygen emission lines. Carbon-oxygen white dwarfs rarely show nitrogen emission or absorption lines; in the process of producing a carbon-oxygen (CO) white dwarf, the core nitrogen is usually consumed almost entirely in the helium burning phase. Helium white dwarfs can contain substantial nitrogen, but helium white dwarfs are low mass objects formed through a binary evolutionary pathway that causes the atmosphere of a low mass evolved star to be ejected or transferred before the nuclear burning runs its course. As low mass objects, extreme fine tuning of the impact parameter of their interactions with an intermediate mass black hole is needed to allow them to be tidally disrupted, rather than tidally detonated (Rosswog et al. 2009). While no helium lines were found in the source spectrum, we show below that this is not a serious constraint on the amount of helium present, as there are plausible ranges for plasma temperature and ionization parameter for which helium can be the dominant species, but no helium lines will be detected.

4 AN ALTERNATIVE EXPLANATION: RCB STARS

There are three closely related classes of stars which are nearly hydrogen-free and which have much larger ratios of nitrogen to oxygen than do white dwarfs – R Corona Borealis (RCB) stars, extreme helium (EHe) stars and hydrogen-deficient carbon (HdC) stars (although we note that some authors consider the RCB stars to be a subclass of the HdC stars – e.g. Warner 1967). The prevailing formation mechanism for these classes is the merger of a He WD with a CO WD (e.g. Webbink 1984; Warner 1967; Clayton et al. 2007; Garcia-Hernandez et al. 2009), but there are alternative suggestions that single star evolution can produce a "final flash" of helium burning (Iben et al. 1996). Since the formation of RCB stars relies on a process related to close binary evolution, and the production of He white dwarfs can be enhanced by stellar collisions, one might expect an overabundance of RCB stars and HdC stars in globular clusters, in the same way that X-ray binaries are overabundant in dense globular clusters compared with field star populations. There is some evidence that globular clusters contain substantial populations of stars with strongly enhanced carbon in their atmospheres (e.g. Strom & Strom 1971; Zinn 1973), but such studies are anecdotal at the present time. The abundance patterns in those stars are generally attributed to dredge-up, rather than mergers, but binary evolutionary processes may be necessary (e.g. Lucatello et al. 2005). We are not aware of any systematic search for RCB, EHe or HdC stars in globular clusters – although as discussed below in section 4.3, some of the surveys for variable stars in globular clusters would have turned up some of the known RCB stars (see e.g. Clement et al. 2001).

4.1 Photoionization calculation

We use the XSTAR version 2.2 photoionization package (Kallman & Bautista 2001) to test whether feasible parameter values can yield reasonable emission line spectra. We start from the assumption that an RCB star is located somewhere in the globular cluster core, and its wind is being photoionized by the bright X-ray source. There are many free parameters in play for a system of this kind, so we apply a trial-and-error approach to find a plausible set of parameters that reproduces the observed optical spectrum to within a factor of a few. Because many of the parameters are nearly degenerate with one another and, apart from upper limits we have only two constraints (since the ratio of the strengths of the lines within the doublets is fixed by atomic physics), we can state with near certainty that the parameter values here are *not* unique.

We start from the assumption that the photoionized gas will have chemical composition roughly similar to that of the RCB stars (see e.g. Garcia-Hernandez et al. 2009). We set the abundances in XSTAR for helium to 4 times the solar abundance, for carbon to 10 times the solar abundance, nfor itrogen to 30 times the solar abundance and for oxygen to 5 times the solar abundance. We note that the study of Garcia-Hernandez allowed for a large range of oxygen and helium abundance but a small range for the other parameters. We leave out the lines from the heavier elements because they are relatively low in abundance and are not reported to have been seen, and because XSTAR calculations are sped up significantly by setting some abundances to zero. We set the temperature of the plasma to 7500 K (a typical temperature for warm RCB stars), then density to 10^3 particles cm^{-3}, the ionizing source to be a 4×10^6 K blackbody with luminosity 2×10^{39} ergs/sec, the ionization parameter Ξ to $10^{0.5}$, and the column density to 2×10^{19} cm^{-2}. The emission in this model comes from a thin shell at a radius of 8×10^{17} cm from the X-ray source. For this set of parameters, we find

$L_{6584} = 2.6 \times 10^{35}$ ergs/sec, L_{5007} is $1.1{\times}10^{35}$ ergs/sec, and the strongest optical line from a species not reported by I10 is the He I λ 4686 line, with $L = 4 \times 10^{34}$, well below the detection threshold in the spectra shown by I10. The calculations are thus in reasonably good agreement with the observed data, but the thinness of the shell, about 2×10^{16} cm is difficult to explain in a physically viable scenario.

We can alternatively consider the case where a stellar wind is being ionized. In this case, the wind is likely to subtend only a fraction of the solid angle seen from the accretor. XSTAR assumes spherical symmetry, so the calculation done will have to be a crude approaximation of the realistic geometry. Larger column densities are necessary in this case, but also, the large column densities can exist without affecting the X-ray spectrum of the source, since the column need not be between the observer and the X-ray source. The region where $\delta R \sim R$ should contribute most strongly to the observed emission. The inner regions will have small solid angles contributing, and the outer regions will have low densities due to the R^{-2} dependence of stellar wind density. We run XSTAR again, with a density of 400 particles cm^{-3}, column density to 3×10^{20} cm^{-2}, and log Ξ=0.75, and all other parameter values as above. The range of radii in the calculations then extends from 9×10^{17} to 1.7×10^{18} cm^{-2}. This calculation yields line luminosities of 5×10^{35} and 3×10^{35} ergs/sec, for the brighter lines of [N II] and [O III], respectively, after accounting for the fact that only about 10% of the solid angle on the sky is emitting. We can then compute the mass loss rate expected from the wind of an RCB star if its density is 400 cm^{-3} a distance 4×10^{17} cm out, and find that it will be about 10^{-5} $M_\odot$ per year, towards the upper end of the range observed from these objects. The gas should reach this radius on a timescale of a few thousand years, again, well within reasonable values for the lifetimes of these stars. Given that an acceptable solution has been found, and that the degeneracies allow other parameter values, it is clear that if RCB stars are abundant enough in globular clusters, it is plausible for the observed optical emission lines to come from photoionization of an RCB wind. We also note that the winds from RCB stars typically are $\sim 100 - 200$ km/sec in velocity (e.g. Clayton et al. 1994; Clayton et al. 2003), only slightly faster than the HWHM reported in I10.

The winds from RCB stars are probably driven by radiation pressure on dust (see e.g. Clayton et al. 2003), which then drags the gas along. This might then modify the expected photoionization signatures expected. We do not think this is a likely scenario, since we have assumed a temperature of 7500 K for the gas – a temperature at which the dust would be sublimated before travelling the $\sim$ light year out to the region in which the photoionized emission lines are produced.

4.2 The black hole mass of the photoionzing source

The implications for the mass of the black hole doing the photoionizing are weak. X-ray sources at luminosities of 2×10^{39} ergs/sec in the Milky Way are often found to be in the "very high" spectral state, in which their spectra can be dominated by a $\Gamma \approx 2.7$ power law, in good agreement with the spectrum presented by I10. On the other hand, if one takes the best disc blackbody fit from I10, one finds that the inner disc radius should be about 1500 km, assuming a colour correction factor of about 3 (see e.g. Davis et al. 2005), and assuming the disc is observed face-on. This would correspond to a black hole of $\sim 100 - 1000$ $M_\odot$, depending on the inclination angle – the lower end of the range would imply a Schwarzschild black hole observed pole-on, while the upper end of the range would imply a Kerr black hole viewed close to edge-on. The upper end of the range is disfavored by the fact that stellar mass black holes (Maccarone 2003) and active galactic nuclei (Ho 1999; Maccarone, Gallo & Fender 2003) tend to have hard power law spectra below a few percent of their Eddington luminosities. The soft X-ray spectrum is thus not a diagnostic of whether the accretor is of stellar or intermediate mass.

We also consider the possibility that the RCB star ejecta could be the mass supply to an intermediate mass black hole, so that no additional bright X-ray source would need to be produced in the cluster. Gas within $GM/(v_w^2{+}c_s^2)$ can be accreted onto the black hole, in a manner similar to Bondi accretion. This yields $R_{acc} = 10^{15}(M/300M_\odot)$ cm. At that radius, the wind density will be ~ 10 cm^{-3} at this radius. The Bondi rate will then be $\sim 10^{14}$ g/sec – far too low to account for the observed X-ray luminosity, even before accounting for the fact that the Bondi rate seems to overestimate observed luminosities by factors of $10 - 100$ (Perna et al. 2003; Pellegrini 2005).

4.3 Observable tests of the RCB hypothesis

A potential key diagnostic is the ratio of ^{18}O to ^{16}O. As predicted by Warner (1967), the hydrogen-deficient carbon stars tend to have about 2-3 times as much ^{18}O as ^{16}O (Garcia-Hernandez et al. 2009). Most of the RCB stars show 3-20 times as much ^{16}O as ^{18}O (Clayton et al. 2007; Garcia-Hernandez et al. 2009) – still well above the solar value (e.g. Collier et al. 1998). Oxygen isotopic abundances in stars are usually measured from molecular bands, but this is not possible for the case of CXOJ033831.8 - 352604. It is unlikely that the isotopic shift will be measurable in the 5007 line itself, especially if ^{16}O is the dominant species, and merely not as dominant as it normally is. We were not able to find any calculations in the literature for the magnitude of the isotopic shift for [O III]λ 5007, but were able to find that the shift between ^{11}B III and ^{10}B III is about 1 part in 50000 (Litzen & Kling 1998). The fractional mass difference for ^{18}O versus ^{16}O is slightly larger, but the B III transition takes place closer to the nucleus. The magnitude of the wavelength shift is likely to be too small to see for the [O III]λ 5007 given the broadening of 70 km/sec reported by I10, but without a careful calculation of the wavelength shift expected for the isotopic difference, it is not clear whether a precise centroiding of the [O III] might be useful – the centroiding of the line in I10 is likely to be accurate to only about 5 km/sec – probably larger than the isotopic shift, especially after weighting by the expected ^{16}O/^{18}O.

A few other strong lines are expected, based on our XSTAR simulations, but outside the optical bandpass used by I10. The strongest line should be the 26 μm [O IV] line, and the strongest line observable with a ground-based CCD should be the 10830 Å line of He I, which should have a flux about 10 times lower than those of the stronger components

of the [O III] and [N II] doublets (but only a factor of about two weaker than the [O III] λ 4959 Åline). The [N III] line at 57 μm is one of the strongest lines from the source – just weaker than [N II], and just stronger than [O III], but just falls within the bandpass of Herschel, and is about 1000 times too weak for Herschel to detect. A strong O VII line at 22 Å should also be present, but again, will have a line luminosity well below the detection thresholds for existing instruments in the X-rays. It thus may be possible, with very long integrations, to detect He I, but the main prediction of the model is that other spectral lines will be very hard to detect.

The idea has an alternative possible test – whether there is a sufficiently large population of RCB stars in the Galactic globular cluster population. It has been estimated that the total Galactic population of RCB stars is about 3200 by scaling up the much better constrained LMC population size by the ratio of stellar masses (Alcock et al. 2001). Since only about 0.1% of the Galactic stellar mass is in globular clusters, one would then find that there should be only a few RCB stars in the entire Galactic globular cluster population. However, if the double degenerate scenario for producing these stars is the correct one, then one should expect a substantial dynamical enhancement in the numbers of RCB stars in globular clusters relative to field star populations. Using the canonical factor of 100 that applies to X-ray binaries, a substantial fraction of the stars in globular clusters that appear to be on the asymptotic giant branch should actually be RCB stars. The recent finding that RCB stars separate themselves from standard AGB star populations very well in the mid-infrared (Tisserand et al. 2010), due to increased dust re-emission, should make searches for them in the cores of globular clusters feasible in the near future using ground-based systems at 10 μm. On the other hand, even a dynamical enhancement of a factor of a few in the fraction of cluster stars that are RCB stars relative to the same fraction for the field would probably be enough to make our scenario plausible – the "extra" RCB stars should be concentrated in cluster cores where the bulk of stellar interactions take place, and should additionally be concentrated in the most massive clusters, since these tend to have the highest stellar interaction rates (e.g. Smits et al. 2006). In the context of our proposed scenario, it will be possible to make an estimate of the dynamical enhancement of RCB stars in globular clusters once a large number of spectra of globular clusters with bright X-ray sources have been published. At the present time, the sample of such objects is small, and possibly biased towards the clusters with emission lines.

We do note that there have been surveys for variable stars in globular clusters, and that some of these surveys have been made over time baselines of a decade or more (e.g. Sawyer Hogg 1980; Clement et al. 2001). These surveys make it clear that there is not a large population of RCB stars which fade as frequently as the RCB stars which have been discovered to date. Given the diversity of RCB stars in terms of how frequently they show fading events, however, it is not clear whether there is a sizeable population of RCB stars whose fading events are infrequent enough to have been missed so far. There are RCB stars which have shown only one fading event over long durations (e.g. XX Cam – one in over 100 years; UV Cas – one in over 70 years and Y Mus – one in over 40 years – see Jurcsik 1996), suggesting that there may very well be some which show very infrequent fading events, and that the typical timescales on which fading events happen for the well know RCB stars are significant underestimates of the typical intervals between fading events for the population of RCB stars as a whole. Additionally, the OGLE lightcurves of known RCB stars often vary by a tenth of a magnitude or less over extended periods between fading events (e.g. Tisserand et al. 2010), which could lead to misclassification as non-variable stars or irregular/long period variables in past surveys of globular clusters for variable stars.

Regardless, the scenario we propose does not require an overabundance of RCB stars in globular clusters of the same factor of 100 found for X-ray binaries. In fact, if the overabundance were that large, we would expect to find spectral lines like those reported by I10 in a very large fraction of globular clusters with bright X-ray sources. At the present time, such studies are largely anecdotal, but only one cluster has shown such lines. Our scenario merely requires that there be some overabundance of RCB stars formed through dynamical interactions, and that these stars remain in the cores of their clusters after formation. The factor of enhancement required will become clear only after a large sample of spectra of clusters with $L_X \sim 10^{39}$ ergs/sec X-ray sources has been made, and the results of those searches (including non-detections) are reported.

5 CONCLUSIONS

We have shown that the combination of strong nitrogen and oxygen emission lines from CXOJ033831.8 - 352604, coupled with a lack of hydrogen and helium emission lines can be well explained if the cluster contains a bright X-ray source near its center photoionizing the wind of an RCB star. The scenario makes no requirements on the mass of the central black hole, and the past X-ray spectral information is inconclusive on this point – thus the case for an intermediate mass black hole previously made is substantially weakened by this new possibility. If the scenario proposed here is correct, then it is highly likely that the formation rate of RCB stars in globular clusters is at least moderately dynamically enhanced.

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